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Displacement Control of Conjugated Polymer Actuator using Self Tuning Regulator

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***Abstract*—Conjugated polymers are used as smart actuators in the field of robotics and bio medical applications. Commonly used polymers in actuation field are polypyrrole and polyaniline. Application of electrical stimuli on these polymer results in drastic changes in chemical, electrical and mechanical properties. Also when operating in air, the actuation behavior shows significant variation due to solvent evaporation and they are difficult to get controlled. As the system parameters varies, a static model-based controller cannot give satisfactory output performance .So this paper proposes an adaptive self- tuning regulator control methodology to enhance the positioning ability of conjugated polymer actuators.**

Index Terms*—Conjugated polymer actuator, Diffusive-elastic –metal model, Self-tuning regulator.

I. INTRODUCTION

Conjugated polymer belongs to the class of electroactive polymers which are also known as artificial muscles. The term conjugation is given due to the presence of alternative single and double carbon bonds in the polymer. Based on different fabrication form, different configuration of the actuators can be obtained namely: linear extenders, bilayer benders, and trilayer benders. These polymers have low power consumption, inherently compliant structure, light weight and are simple in construction. Their operation principle is easy to understand and possess noiseless operation. Another advantage of conjugated polymer actuator is that they require very low actuation voltage usually in the range less than one. So they find wide variety of application in biomedical and robotics. Different kinds of conjugated polymers are used for actuation purpose. Among them polypyrrole (PPy) and polyaniline (PANI) are most investigated polymers due to their good chemical stability and substantial strains. In this paper a trilayer polypyrole actuator is considered.

The working of conjugated polymer actuators is based on the oxidation and reduction phases which mainly deals with the diffusion or migration of the ions at the polymer electrodes. Mass transport of ions and solvent during reduction/oxidation (redox) is considered as the primary mechanism. It is responsible for volumetric change and the actuation capability of conjugated polymers. Ion transfer inside the polymer actuators is based on two main mechanisms namely diffusion and drift. Contraction and expansion results from ions transfer into and out of the polymer from a surrounding electrolyte.

For getting very best performance from a given class of actuators, it is crucial to understand, select, and design these materials with optimized properties.In order to use the conjugated polymer actuator in various applications, it is desirable to have the suitable models of it which can predict quasi static and dynamic actuation performance. It should be in terms of intrinsic material parameters and actuator dimensions. Such models will be useful in feasibility analysis, design optimization, and in the control of actuator. Modeling and geometry optimization of bending curvature and force output for trilayer PPy actuators was investigated by Alici[2,3,4].The bending curvature for bilayer PPy microactuators of different dimensions were modeled by Christophersen[8].

Polymer actuators are often subjected to varying environmental conditions. This may lead to changes in the plant parameters. In such situations for proper control action ,the controller should adapt to the new conditions . For many applications it is very important to precisely control the displacement of polymer actuator. To speed up the transient responses of an polyaniline actuator ,a proportional controller was designed by Qi et al.[6] .By an inversion based feed forward control method the positioning ability of the tri-layer actuators can be significantly improved . P. Madden treated the actuation dynamics as a first-order system and designed a PID controller for a polypyrrole actuator[7]. Bowers did studies on control of conjugated polymers using PID and adaptive. [9].

The full order infinite dimensional model of the polymer actuator is proposed by madden [10] which is also known as the Diffusive Elastic Model . This model captures all the main electrochemical dynamics of the actuator during redox processes. For real time control analysis As this full order model is infinite dimensional it is difficult to be used with real time control analysis. So a simple model structure is derived from it through model reduction which captures all essential actuation dynamics. So it enables compact, embedded controller implementation for various micro, robotic and biomedical applications.

The actuation behavior of the polymer shows significant variation due to solvent evaporation. So when classical fixed control methods are used desired response cannot be achieved. The controller parameters have to be varied according to the variation in plant parameters. So a self -tuning regulator is used to consider the effect of plant parameter variation. Its designed based on the identified parameters to make the closed-loop system follow a reference model. To identify the parameters of the reduced model recursive-least squares algorithm is used.

Simulations are done in matlab. The responses obtained are compared with fixed model following controller. This paper is organized as follows. In section II the working of trilayer PPy actuator and in section III its infinite-dimensional full order model is introduced. In section IV model reduction is presented. The design of self tuning regulator is given in section V. Finally simulation results are shown in Section VI.

II. WORKING OF TRILAYER POLYMER ACTUATOR

Fig.1 shows the sectional view of trilayer polymer actuator. Both ends of the actuator consists of Polypyrrole layers. Middle portion consists of porous polyvinylidene fluoride which serves as backing material and storage tank of the electrolyte. The electrolyte used in this actuator is Tetrabutylammonium hexafluorophosphate in the solvent of propylene carbonate. When potential difference between the polymer and electrolyte is changed, the volume of the conjugated polymer gets changed. This principle can be used to produce bending motion in tri layer configuration. When voltage is applied across the actuator the anode side get oxidized and cathode side is reduced. An anion-transporting conjugate polymer will expand during oxidation and contract during reduction, while a cation transporting polymer will be the opposite behavior. The chemical equations during redox process can be given as:

Oxidation: $PPy + PF6^- \rightarrow PPy + PF6^- + e^-$

Reduction: $PPy + PF6^- + e^- \rightarrow PPy + PF6^-$

Here PPy represents the neutral state of PPy and PPy+ is the oxidized state. PPy+ PF6- indicates that PF6- is incorporated into the polymer. Oxidation takes place at the anode side and reduction at the cathode side. The layer get oxidized absorbs anions and expands while the reduced layer give up anions and contracts. This will result in the bending of the polymer actuator

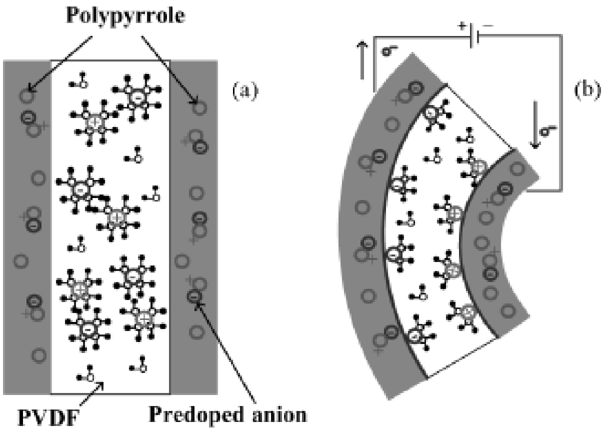

Fig 1: (a) Sectional view of trilayer polymer actuator.
(b) Actuator bending on application of voltage.

III. MODELLING OF TRILAYER POLYMER ACTUATOR

The model of the actuator is also known as electrochemomechanical model which contains electrical, chemical, and mechanical parameters . The complete actuator model consists of three modules. First one is the electrical admittance module relating the current flowing to the voltage input. Second is the electromechanical coupling module which relates the generated stress in terms of the transferred charge and finally the mechanical module connecting the stress to the displacement or force output.

i. Admittance Module

It is desired to obtain the electrical admittance module relating the current (and thus the charge transferred) to the voltage input in order to obtain the complete actuation model.

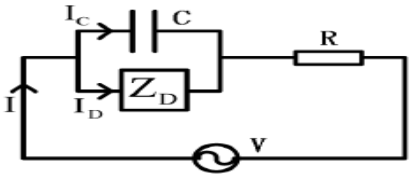

Fig 2: Equivalent circuit model for polymer impedance

An equivalent circuit model of the actuator is depicted in Fig 2 .It shows the electrochemical parameters involved in the polymer. Current passes through the actuator layers when a potential difference is applied between two polymer layers. Under the potential difference, the anions in the electrolyte migrate toward the polymer, which results in double layer charges at the polymer/electrolyte interface - like a double-layer capacitance with an equivalent thickness of δ. In the figure C denotes the double-layer capacitance at the polymer/electrolyte interface and R is the electrolyte and contact resistance and Z_D represents the diffusion impedance. In the laplace domain, the total current I (s) in the circuit is

$$I(s) = I_C(s) + I_D(s) \tag{1}$$

The Kirchhoff's voltage law gives

$$V(s) = I(s)\,R + \frac{1}{sC} I_C(s) \tag{2}$$

From Fick's law of diffusion,

$$I_D(s) = -FAD \frac{\partial c}{\partial x}(x, s) \quad \text{at } x = 0 \tag{3}$$

where A is the surface area of the polymer, F is the Faraday constant, D is the diffusion coefficient, and $\frac{\partial c}{\partial x}$ (x,s) at x = 0 represents the gradient of ion concentration at the interface. Assume that the double layer has a thickness δ and that the ion concentration within the (thin) double-layer is uniform, which equals c (0,s). Then Qc(s) = F A δ c(0,s)

$$I_C(s) = s\,Q_C(s) = F\,A\,\delta\,s\,c(0,s) \tag{4}$$

The diffusion equation in the time domain is

$$\frac{\partial c}{\partial t} = D\,\frac{\partial^2 c}{\partial x^2},\ 0 < x < h \tag{5}$$

In the frequency domain, (5) is written as

$$\frac{s}{D}\,c\,(x,s) = \frac{\partial^2 c(x,s)}{\partial x^2} \tag{6}$$

The last equation needed is the boundary condition

$$\frac{\partial c}{\partial x}(x, s) = 0 \ \text{ at } x = h \tag{7}$$

Using eqn (1-7) the admittance model of a conjugated polymer with one side in contact with electrolyte is obtained as

$$Y_1(s) = \frac{I(s)}{V(s)} = \frac{s\left[\frac{\sqrt{D}}{\delta} \tan h\left(h\sqrt{\frac{s}{D}}\right) + \sqrt{s}\right]}{\sqrt{\frac{s}{C}} + Rs^{3/2} + R\frac{\sqrt{D}}{\delta}\, s \tanh(h\sqrt{\frac{s}{D}})} \tag{8}$$

The voltage input V(s) is applied across two double-layers, and therefore, the admittance Y(s) will be half of (8) which gives

$$Y(s) = \frac{I(s)}{V(s)} = \frac{1}{2}\,\frac{s\left[\frac{\sqrt{D}}{\delta} \tan h\left(h\sqrt{\frac{s}{D}}\right) + \sqrt{s}\right]}{\sqrt{\frac{s}{C}} + Rs^{3/2} + R\frac{\sqrt{D}}{\delta}\, s \tanh(h\sqrt{\frac{s}{D}})} \tag{9}$$

ii. Electromechanical Coupling

The induced in-plane strain ε is proportional to the density ρ of the transferred charges

$$\epsilon = \alpha\rho \tag{10}$$

Density $\rho(s)$ is obtained by

$$\rho\,(s) = \frac{I(s)}{sWLh} \tag{11}$$

iii. Mechanical Module

The beam curvature κ can be obtained as

$$\kappa = \frac{3\alpha}{2h_{pvdf}}\;\frac{[1+\frac{h}{h_{pvdf}}]^2 - 1}{[1+\frac{h}{h_{pvdf}}]^3 + \frac{E_{pvdf}}{E_{ppy}} - 1}\,\rho \tag{12}$$

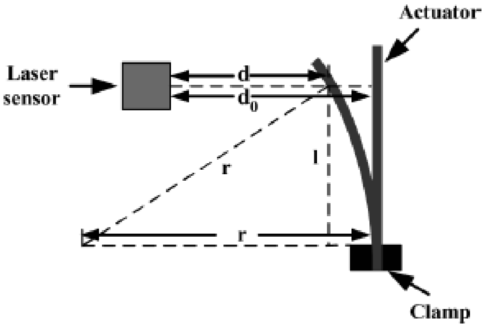

Fig 3: Geometric relationship between the beam curvature and the tip displacement

$$\text{Also } \kappa = \frac{1}{r} = \frac{2y}{y^2 + l^2} \tag{13}$$

Using (9-13)

$$\frac{y(s)}{V(s)} = C_m\,\frac{\frac{\sqrt{D}}{\delta} \tanh\,(h\sqrt{\frac{s}{D}}) + \sqrt{s}}{\frac{\sqrt{s}}{C} + R\,s^{3/2} + R\frac{\sqrt{D}}{\delta}\, s \tanh(h\sqrt{\frac{s}{D}})} \tag{14}$$

IV. MODEL REDUCTION

Eqn (14) can be re written as

$$\frac{y(s)}{V(s)} = \frac{C_m}{sR + \frac{1}{C(1+\frac{2D}{h\delta}\ \sum_{n=0}^{\infty}\frac{1}{s+\pi^2(2n+1)^2 D(2h)^{-2}})}} \tag{15}$$

Discarding terms with n ≥ 2, results in third-order system for the actuator.

$$\frac{y(s)}{V(s)} = \frac{b_1' s^2 + b_2' s + b_3'}{s^3 + a_1' s^2 + a_2' s + a_3'} \tag{16}$$

This third order system has one pole and one zero that are located far to the left of the imaginary axis comparing to other poles and zeros, and therefore,they can be neglected and the model can be further reduced . The final reduced model for the trilayer actuator is obtained as

$$\frac{y(s)}{V(s)} = \frac{b_1\, s+ b_2}{s^2+ a_1 s+ a_2} \qquad (17)$$

V. SELF TUNING REGULATOR

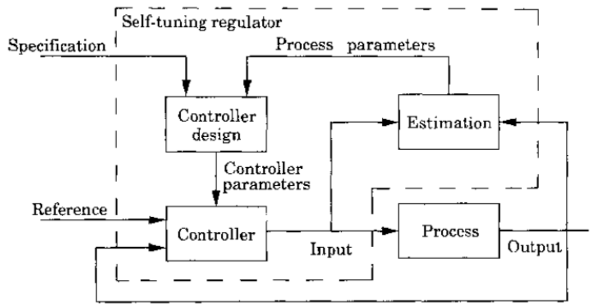

Fig 4: Self Tuning Regulator

As there is variation in actuation behavior, fixed model based controller cannot be used in this case. Here a self-tuning regulator is implemented which estimates the parameters and based on these estimated parameters controller is designed. The main advantage of using STRs as adaptive controllers lies in the large number of combinations of schemes can be implemented, based on the needs of the plant.

The entire closed loop system should behave like a model G_m. A low-pass filter is used to filter the noises in the output signal before the output is sent to the self-tuning regulator In the estimation the regressor is given by

$$\varphi^T(t) = [-\frac{d}{dt}L^{-1}\left(H_f(s)y(s)\right) \quad -L^{-1}\left(H_f(s)y(s)\right) \quad \frac{d}{dt}L^{-1}(H_f(s)\,V(s) \quad L^{-1}(H_f(s)\,V(s)))] \qquad (18)$$

where $L^{-1}(.)$ denotes the inverse laplace transform and $H_f(s)$ is a filter which prevents direct differentiation of signals.

$$\hat{\theta} = [\,\widehat{a_1}\ \widehat{a_2}\ \widehat{b_1}\ \widehat{b_2}\,]^T$$

$$P(t) = [\,\varphi^T(t)\varphi(t)]^{-1} \qquad (19)$$

$$\frac{dP(t)}{dt} = \beta\, P(t) - P(t)\,\varphi(t)\varphi^T(t)P(t) \qquad (20)$$

$$e(t) = y(t) - \varphi^T(t)\hat{\theta}(t) \qquad (21)$$

Desired closed loop transfer function is obtained as

$$G_m(s) = \frac{B_m(s)}{A_m(s)} = \frac{b_{1m}s+ b_{2m}}{s^2+ a_{1m}s+a_{2m}} \qquad (22)$$

The controller has to make the closed loop system follow $G_m(s)$

$$V(s) = \frac{b_{1m}s + b_{2m}}{\widehat{b_1}s+ \widehat{b_2}}\, r(s) - \frac{(a_{1m}- \widehat{a_1})s +(a_{2m}- \widehat{a_2})}{\widehat{b_1}s+ \widehat{b_2}}\, y(s) \qquad (23)$$

In the reduced order system the two poles and the zero are all negative. So the parameters a1, a2, b1, and b2 must all be positive, which are bounded as [m, M]. The update rules to incorporate parameter projection is given by :

$$\frac{d\hat{\theta}_i(t)}{dt} =$$

$$\begin{cases} 0 & if\ \hat{\theta}_i(t) = M\ and\ [P(t)\varphi(t)e(t)]_i > 0 \\ 0 & if\ \hat{\theta}_i(t) = m\ and\ [P(t)\varphi(t)e(t)]_i < 0 \\ [P(t)\varphi(t)e(t)]_i & otherwise \end{cases} \qquad (24)$$

VI .SIMULATION RESULTS

The performance of the proposed polymer is illustrated. In this section, The simulation results are achieved with the MATLAB software. The parameter values of the polymer actuator are given in the table 1.

TABLE 1 : Parameter Values

Parameter	Value
D	2×10^{-10} m^2/s
h	30 µm
R	15Ω
δ	25 nm
C	5.33×10^{-5} F

The diffusion coefficient of polymer actuator varies with time. Simulation is done with different values of diffusion coefficient. For simulation the polymer actuator is assumed in the nominal condition up to 10 seconds. After that instant the diffusion coefficient of the plant is reduced by 20%. Fig 5 shows output waveform in the nominal case and with parameter variation . From the figure it is clear that even though parameter variation occurs in the plant, desired response is obtained.

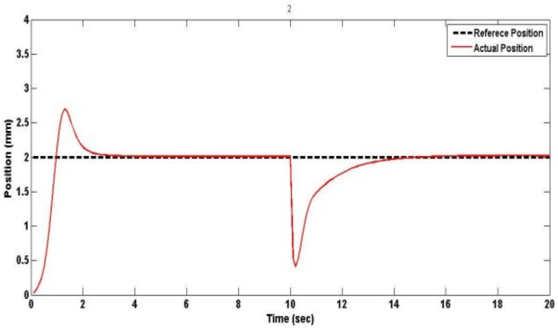

Fig 5: Adaptive control of polymer actuator with variation in plant parameter

Based on the desired dynamic responses and actuation constraints of the actuator the reference model for the system is chosen. For comparison purpose a fixed model following controller is implemented. The model following controller is constructed as in (23), but the controller parameters are not updated ie. the parameters of the controller is not updated.

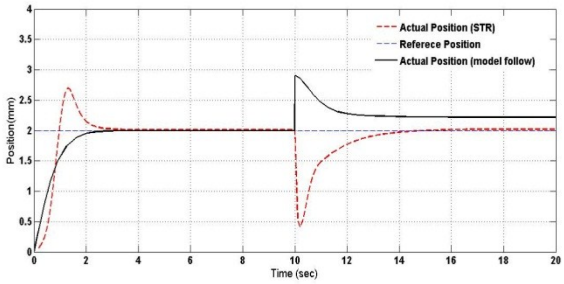

Fig 6: Comparison of output waveform using STR and fixed model follow controller

Fig.6 shows a simulation comparison of output waveforms in the nominal case and with parameter variation using self-tuning regulator and conventional fixed model follow controller. It can be seen that both of the two control schemes are good and can reproduce the reference signal accurately in the nominal case. Parameter variation occurs in the plant after 10sec ie. the diffusion coefficient of the polymer is reduced by 20%. In the presence of parameter variation the results are quite different. With parameter variation self-tuning regulator can track the reference signal accurately but the performance of model following control got deteriorated.

.VII CONCLUSION

In this paper a reduced second order model of the polymer is obtained from the infinite dimensional model. All the parameters of reduced model can be related to fundamental physical parameters of the full model. Simulation results shows that adaptive control considers the parameter variation that occurs in the system. The controller parameters in the self tuning regulator are updated accordingly and so it can track the reference signal accurately than a conventional fixed model follow controller.

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